Marine and Petroleum Geology 69 (2016) 241–261

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Upper-plate magma-poor rifted margins: Stratigraphic architecture and structural evolution

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ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form
21 October 2015
Accepted 26 October 2015
Available online 30 October 2015

Keywords:
Upper plate magma-poor rifted margins
Hyper-extension
Tectono-stratigraphic evolution
Crustal architecture
Ocean–continent transition

ABSTRACT

Although it is generally accepted that many distal, magma-poor rifted margins are asymmetric and can be divided into lower and upper plate margins, little is known about the details of how and when this asymmetry evolves and how upper and lower plate margins can be distinguished. This is due to the fact that most papers focused on the so called lower plate margins, while the upper plate margins remained less well understood, mainly due to the lack of public accessible drill hole data. The aim of this paper is to provide a first order description of the global architecture and stratigraphic evolution of an upper plate, magma-poor rifted margin. In order to provide such a template, we focused on 2 seismic sections, the ION-1000 line (East Indian margin), and the SCREECH 2 line (Newfoundland margin) and describe key, km-scale outcrops from the fossil European margin exposed in the Western/Central Alps, all of which document classical upper plate margins. Based on these data we show that upper plate magma-poor rifted margins can be characterized by a staircase type architecture with terraces (T_1, T_2, T_3) and ramps (R_1, R_2) that result as a consequence of an evolution through a coupling, exhumation and breakup stage. We also defined key stratigraphic levels that we try to link with the evolution of the margin which enables us to link the tectonic evolution with the creation of accommodation space and formation of the staircase architecture that characterizes the upper plate margin. From these observations we develop a conceptual model for the evolution of upper-plate margins and discuss the applicability of this model for different strain rates, rates of subsidence and sedimentation rates.

1. Introduction

During the last decades research on rift systems leading to plate separation and formation of oceanic domains went through several paradigm shifts. In the late seventies and early eighties, debates were mostly related to pure-*vs.* simple-shear models and the question if lithospheric scale detachment faults exist or not. In the late eighties and early nineties, the question about volcanic *vs.* non-volcanic rifting dominated the research on rifted margins. These earlier models were either based on physics (e.g. McKenzie, 1978; Buck, 1991), on field observations (e.g. Basin and Range; Wernicke, 1981) or some few drill holes and low quality seismic sections. The increasing number of high quality long offset seismic data, mainly due to the increasing interest of industry to explore the deep-water parts of rifted margins, enabled to answer some of these previous questions. Moreover, the development of dynamic modeling enabled to get a better understanding of the crustal-scale processes and to test some of the basic assumptions made in extensional tectonics. Key questions addressed at present are related to the coupling/decoupling between crust and mantle and lithosphere and asthenosphere during advanced rifting, the importance of magma and fluids for the evolution of the rheology at the transition from rifting to seafloor spreading, and the relationships between extension and creation of accommodation space in time and space in hyper-extended systems. In order to find answers to these questions, some of the basic assumptions of extensional systems that form the foundation of existing models need to be scrutinized and new interpretations are necessary to explain some of the fundamental observations made in the new data sets.

The aim of this paper is to describe the first order stratigraphic architecture and structural evolution of so called “upper plate” magma-poor rifted margins. We focus on three examples that we consider as typical upper-plate magma-poor rifted margins: one fragmented during Alpine collision, but partly exposed in the

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http://dx.doi.org/10.1016/j.marpetgeo.2015.10.020
0264-8172/

Western and Central Alps in Western Europe, one seismically imaged offshore eastern India, and a last one seismically imaged and drilled offshore Newfoundland. Because none of the 3 examples provides a complete dataset and cannot therefore be used to explain the detailed relationship between extension and creation of accommodation space, we integrate the different observations/data in a "type" section in order to define and discuss the first order tectono-stratigraphic evolution of upper plate margins. Initial assumptions that are made in this study are that: 1) margins show first order architectural characteristics and processes that can be found and described, and 2) the "type" section proposed here represents an idealized, non-unique section, which does not exist in nature, but includes the key building blocks and structural and stratigraphic relationships that characterize upper plate, magma-poor rifted margins. We are aware that our approach suffers of some limitations that are important to consider when the results and concepts established here are used to describe a margin with a defined history and inheritance. The main limitations are to: 1) not consider the nature of the sediments filling the accommodation space, 2) to limit to magma-poor systems, and 3) to ignore the geological inheritance and the 3D lateral architecture of a margin segment, which is related to a variability of the large-scale structure along strike. Indeed, the described characteristics may vary along strike and may therefore also be geographically dependent. Thus, rather than to explain a detailed description of one particular upper plate margin, here we try to develop a conceptual framework to make first order descriptions and predictions of the structural and stratigraphic evolution of an upper plate, magma-poor rifted margin. The idea is to create a template and to develop a methodology to recognize and interpret magma-poor, upper plate rifted margins.

2. Models, concepts, terminology and methodology

2.1. Development of models and concepts

The description of rift systems is strongly linked to two end-member models, the McKenzie (1978) and Wernicke (1981) models that describe two fundamental different ways of how strain is partitioned in the crust and lithosphere. The McKenzie model is depth-uniform and symmetric, assuming that crustal and lithospheric thinning is inversely proportional to horizontal extension. On the contrary the Wernicke model is more conceptual and assumes that deformation in the crust and lithosphere is coupled and fundamentally asymmetric. Based on observations in the Basin and Range and at rifted margins, Lister et al. (1986) proposed a rift model that accounts for a "lower-plate" and an "upper-plate" margin (Fig. 1a). Indeed, several authors found similarities between the Basin and Range tectonics and structures observed at passive margins (e.g.Buck et al., 1988; Pubellier and Ego, 2002; Pubellier et al., 2003). In particular, extensional detachment faults, similar to those well exposed in the Basin and Range, have also been recognized along present-day and fossil rifted margins (Masini et al., 2012 and references in there). Such faults are associated with the formation of metamorphic core-complexes (Crittenden et al., 1980) in the footwall (i.e. the "lower plate") while their hanging wall, (i.e. the "upper plate") is considered as largely brittle and less deformed (Reynolds and Spencer, 1985). However, it's important to note that the hanging-wall is still affected by extensional structures including normal faults and associated shear zones in more ductile crustal levels. In contrast to the McKenzie model that can successfully explain the structural style of North Sea type rift systems, the "upper-lower plate" model of Lister et al. (1986) was used to explain some first order observations made at present-day rifted margins (Fig. 1a). Typically, the Lister model accounts for wide vs. narrow conjugate margins, exhumation of mantle rocks and contrasting subsidence histories observed at both margins.

The archetypal examples of asymmetric, magma-poor rifted margins became the Iberia-Newfoundland conjugate margins (Boillot et al., 1987) and the Alpine Tethys margins exposed in the Alps (Lemoine et al., 1987). However, since the "upper-lower plate" model of Lister was intimately linked to the Wernicke model, i.e. to Basin and Range tectonics and to low-angle extensional detachment faults that violate first order mechanical principles, many researchers discarded this model. Moreover, since most of the rift basins located at the proximal domains at conjugate rifted margins look relatively symmetrical and can be explained by pure shear, Driscoll and Karner (1998) introduced the so-called "upper-plate" paradox. Nevertheless, Huismans and Beaumont (2002) showed that the capacity of an extending crust to couple or decouple deformation on a crustal scale depends, at a first order, on the rates of extension and the rheology or the lithosphere. These parameters therefore have a strong control on the symmetry vs. asymmetry of rifted margins. Recent studies shed a new light on the lateral variation of the architecture of rifted margins. Transitions from magma-poor to magma-rich and changes from upper to lower plate can be observed following rifted margins along strike (see Fig. 1b; (Reston, 2009, 2007; Franke, 2013; Peron-Pinvidic et al., 2013)). Nevertheless, on a first order, it appears that magma-rich rifted margins tend to be more symmetric, while magma-poor systems are typically asymmetric in their distal parts. However, observations and dynamic models show that rifted margins are not the result of a single process and/or event, but of polyphase rift events. Lavier and Manatschal (2006) and Péron-Pinvidic and Manatschal (2009) developed a model in which rift systems go through different stages, referred to as stretching, thinning and exhumation modes before breakup occurs (Fig. 2). Peron-Pinvidic and Manatschal (2010), Sutra et al. (2013) and Tugend et al. (2015) described and characterized "building blocks" and "rift domains" that result from the polyphase evolution and can be used to describe the architecture of magma-poor rifted margins.

2.2. Definition of an "upper-plate" margin

As mentioned in the previous section, the "upper-plate" concept, as introduced by Lister et al. (1986) (Fig. 1a), was strongly linked to the Wernicke model and lithospheric-scale extensional detachment faults. Since the existence of such faults was for a long time a matter of debate, in this study we refine the original "upper-plate" concept in order that it can be used to properly describe the evolution of rifted margins in a much wider context. Using the term "upper-plate" already begs the question: upper-plate to what? In its pristine concept, the term "upper-plate" was used as a synonym of "hanging wall" of a major, lithospheric scale extensional detachment fault. However, in contrast to the Basin and Range, where extensional detachments are exposed, at rifted margins these structures are buried underneath thick sediments, magma and water and are split during breakup between the two futures conjugate margins (Fig. 1a). The lower plate usually carries remnants of the former hanging-wall (i.e. extensional allochthons or rafts; (Wernicke, 1981, 1985; Wernicke and Burchfiel, 1982; Davis, 1983). Thus, "upper-plate" does not exclusively refer to the position of a block relative to a major extensional detachment system, but refers to a position in a conjugate magma-poor rifted margin. A second limitation is that "upper" and "lower" do not apply to proximal domains that commonly do not show any asymmetry, neither from the architectural point of view, nor from their subsidence history (Lister et al., 1986; Karner et al., 2003). Therefore the "upper-plate" is limited continental ward by the necking zone, defined by the